# An enshrouded AGN in the merging starburst system Arp 299 revealed by *Beppo*SAX

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## ABSTRACT

Using a long ($\simeq$150 ksec), broad-band (0.1–40 keV) *Beppo*SAX observation of the merging starburst system Arp 299 (=IC 694 + NGC 3690) we found the first unambiguous evidence of the presence of a deeply buried ($N_H \simeq 2.5 \times 10^{24}$ cm$^{-2}$) AGN having an intrinsic luminosity of $L_{0.5-100\ \mathrm{keV}} \simeq 1.9 \times 10^{43}$ erg s$^{-1}$. The X-ray spectral properties of this AGN are discussed in detail as well as the thermal component detected at soft X-ray energies which, most likely, is associated with the starburst.

*Subject headings:* galaxies: active – galaxies: individual (IC 694, NGC 3690) – galaxies: groups (Arp 299) – galaxies: nuclei – galaxies: starburst – X-rays: galaxies

## 1. Introduction

Studies of active objects at IR and X-ray wavelengths indicate that star-formation and AGN activity may be related (Fadda et al. 2002). The triggering mechanism for both phenomena could be the interaction or the merging of gas-rich galaxies. This generates fast compression of the available gas in the inner galactic regions, causing both the onset of a major starburst and the fueling of a central black hole raising the AGN activity (see Combes, 2001 for a recent review). These two processes may proceed with different time scales and once initiated they probably have different lifetimes. Therefore a detailed study of the relative importance of starburst and AGN activity in the nearest (and brightest) objects may have profound impact on the understanding of the evolution and the fate of the gas in the interaction process, on the modeling the cosmological evolution of both AGNs and starburst objects (e.g. Franceschini, Braito and Fadda 2002), and on the evaluation of the contribution of these sources to the energy density of the Universe (e.g. Fabian et al. 1998).

The concomitant AGN and starburst activity is expected to happen in a high-density medium ($N_H \geq 10^{23-24}$ cm$^{-2}$), characterized by high dust extinction of the UV-optical flux and strong photoelectric absorption of the soft X-rays (e.g. Fabian et al. 1998). Therefore, the study of these active phases in galaxies becomes very difficult. Specific examples are NGC 6240 and NGC 4945. Both objects have been classified as LINER and/or starburst galaxies on the basis of optical (Veilleux et al. 1995) and mid-/far-IR (Genzel et al. 1998) spectroscopy. For both objects, however, the *Beppo*SAX PDS observations at $E > 10$ keV have clearly revealed the presence of a deeply buried AGN ($N_H \simeq$ few $\times 10^{24}$ cm$^{-2}$) with a QSO-like intrinsic luminosity in the case of NGC 6240 ($L_{0.5-100 \text{ keV}} \sim 6 \times 10^{44}$ erg s$^{-1}$; Vignati et al. 1999) and a Seyfert-like luminosity in the case of NGC 4945 ($L_{0.5-100 \text{ keV}} \sim 7 \times 10^{42}$ erg s$^{-1}$; Guainazzi et al. 2000). These two examples clearly show that optical and mid-/far-IR spectroscopy may not be sufficient to disentangle starburst activity from AGN activity, which is actually best probed in the hard ($E > 6$ keV, in order to sample also the Fe K$\alpha$ line) X-ray energy band.

To shed light on the starburst-AGN connection and its occurrence we have started a systematic and objective investigation in hard ($E > 6$ keV) X-rays of *a flux-limited sample of IRAS galaxies*. The sample consists of 28 galaxies selected from the *IRAS Cataloged Galaxies and Quasars* (see http://irsa.ipac.caltech.edu/) as having $f_{60\,\mu\text{m}} > 50$ Jy or $f_{25\,\mu\text{m}} > 10$ Jy. We stress here that no other selection criteria (e.g. established presence of an AGN, luminosities, IR colours, etc.) have been applied to the sample definition.

In this letter we present and discuss *Beppo*SAX observations of Arp 299, a merging system (composed of IC 694 and NGC 3690, but simply quoted as NGC 3690 in the IRAS catalogue) located at D = 44 Mpc (z = 0.011; Heckman et al. 1999 - H99), spectroscopically classified as starbursting from optical (Coziol et al. 1998) and mid-/far-IR (Laurent et al. 2000) observations. Its total FIR ($43 - 123\mu$m) luminosity, $2.86 \times 10^{11}\ L_\odot$ (following the recipe in Helou et al. 1988 and using the *IRAS Faint Source Catalogue* fluxes, Moshir et al. 1990), dominates the bolometric luminosity. As shown in this letter the *Beppo*SAX observations unveil a strongly absorbed ($N_H \simeq 2.5 \times 10^{24}$ cm$^{-2}$) AGN with an intrinsic (unabsorbed) luminosity of $L_{0.5-100\ \mathrm{keV}} \simeq 1.9 \times 10^{43}$ erg s$^{-1}$: **this is the first unambiguous evidence of the presence of an AGN in the interacting system Arp 299**. For a detailed description of the system and for a summary of previous multiwavelength observations see Zezas, Georgantopoulos and Ward (1998; ZGW98), H99, Hibbard and Yun (1999), Alonso-Herrero et al. (2000), and Charmandaris, Stacey and Gull (2002). In this paper we assume $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, and $q_0 = 0.5$.

## 2. Observations and data reduction

Arp 299 was observed by *Beppo*SAX (Boella et al. 1997) in 2001 December 14 - 18 for about 150 ksec. In this letter we use data collected from the Low Energy Concentrator Spectrometer (LECS), the Medium Energy Concentrator Spectrometer (MECS) and the Phoswich Detector System (PDS).

The cleaned and linearized data produced by the *Beppo*SAX Scientific Data Center (SDC, see http://www.asdc.asi.it/bepposax) have been analyzed using standard software packages (XSELECT v1.4, FTOOLS v4.2 and XSPEC v11.0). At the best spatial resolution of the *Beppo*SAX instruments ($\sim 2'$), Arp 299 is not resolved; no significant source flux variation was detected over the whole observing period. In the PDS field of view ($\sim 60'$ radius) there are no known and bright (2–10 keV) X-ray sources except Arp 299. In the ROSAT All Sky Survey catalogue we found only two QSOs within $60'$ from Arp 299; given their lower flux and off-axis angle we can exclude them as sources of contamination in the PDS energy range.

To maximize statistics and $S/N$, the LECS and MECS source counts were extracted from a circular region of $4'$ radius; background counts were extracted from high-Galactic latitude "blank" fields (provided by the *Beppo*SAX SDC). The PDS spectrum extracted with the standard pipeline (with the rise-time correction applied) was provided directly by the *Beppo*SAX SDC; the simultaneously measured off-source background was used. In our analysis we took into account only data in the 0.1–4 keV and 1.8–10 keV energy range for the LECS and MECS respectively (as suggested in the *Beppo*SAX Cookbook, Fiore et al. 1999). Spectral channels corresponding to energies 10–40 keV have been used for the PDS data. LECS and MECS (PDS) source counts have been rebinned to have a $S/N > 3$ ($S/N > 2$) in each energy bin. Standard calibration files released by the *Beppo*SAX SDC (September 1997 version) have been used. The LECS to MECS and PDS to MECS normalization factors were allowed to vary in the ranges proposed by the *Beppo*SAX Cookbook. Net exposure times (count rates) are: 63830 s ($0.0087 \pm 0.0004$ cts/s) for the LECS; 177050 s ($0.0124 \pm 0.0003$ cts/s) for the MECS; 75490 s ($0.0852 \pm 0.0187$ cts/s) for the PDS.

## 3. Spectral analysis

Single-component models [1] do not provide an adequate description of the broad-band (0.1–40 keV) spectrum of Arp 299. A single-temperature thermal model or a single unabsorbed power-law model are both rejected at a confidence level greater than 99.9%. Figure 1 shows the ratio between *Beppo*SAX LECS, MECS and PDS data and the best-fit

[1] All models discussed here have been filtered through a foreground Galactic absorption of $N_{H,Gal} = 9.92 \times 10^{19}$ cm$^{-2}$ (Dickey and Lockman 1990). The thermal component(s) have been modelled with the MEKAL model. All quoted errors are at the 90% confidence level for 1 parameter of interest ($\Delta\chi^2 = 2.71$).

unabsorbed power-law model ($\Gamma \sim 1.9$). A bump at $\sim 0.8$ keV, a line-like feature at $\sim 6.4$ keV, and a big bump in the PDS energy range (10–40 keV) are clearly evident. The residuals suggest the presence of a soft thermal component around 0.8 keV, which is a characteristic signature in all known starburst galaxy X-ray spectra (e.g. Dahlem, Weaver and Heckman 1998). **The simultaneous occurrence of a strong line-like structure at $\sim$ 6.4 keV and of a big bump in the PDS energy range is the distinctive spectral signature of an obscured AGN** (Matt et al. 2000).

Given these features, we have performed a broad-band fit which includes: *a)* a soft thermal model; *b)* an unabsorbed power law with photon index $\Gamma$; *c)* a Gaussian emission line at $\sim 6.4$ keV, and *d)* an absorbed[2] power law having the same photon index $\Gamma$. The combination of the spectral components *b)* and *d)* is usually called "leaky-absorber" model where the absorbed power law (accounting here for the PDS energy range) represents the "first order" AGN continuum emerging after transmission through an obscuring cold medium (torus? starburst related dust?). The unabsorbed power law (accounting here for the MECS energy range) represents the primary AGN spectrum scattered into the line of sight by a warm, highly ionized gas located outside the absorbing medium. Furthermore, the residuals (not reported here) still show a clear line-like excess at $\sim 3.5$ keV, which has been modelled with a Gaussian emission line. The results of this best-fit model [3] ($\chi^2$/d.o.f=104.2/118) are reported in Table 1 and are shown in Figure 2.

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[2]Given that the intrinsic $N_H$ is expected to be high ($\sim 10^{24}$ cm$^{-2}$) we have used the PLCABS model (Yaqoob 1997), which describes the X-ray transmission correctly taking into account Compton scattering.

[3]A simpler model described by a power law plus a thermal component and a Gaussian line at $\sim$ 6.4 keV is rejected by the data at a confidence level greater than 99% ($\chi^2$/d.o.f=162.1/122).

## 4. Discussion

### 4.1. The AGN component

The *Beppo*SAX data provide unambiguous evidence of the presence of AGN emission from Arp 299, with an intrinsic (i.e. unabsorbed) luminosity of $L_{0.5-100\ \mathrm{keV}} \simeq 1.9 \times 10^{43}$ erg s$^{-1}$.

The intrinsic power-law photon index ($\Gamma = 1.79^{+0.05}_{-0.03}$) is very similar to that usually observed in Seyfert 1 galaxies (Nandra et al. 1997). The primary continuum is highly absorbed ($N_H = 2.5 \times 10^{24}$ cm$^{-2}$, with a 99% confidence level lower limit of $\sim 1.76 \times 10^{24}$ cm$^{-2}$) and can escape from the absorber only at energies above 10 keV: this indicates that a deeply buried "Compton-thick AGN" lies in the interacting system Arp 299. The scattered flux fraction (given here as the ratio between the normalizations of the unabsorbed and absorbed power law components) implied from the fits is $(5 \pm 3)\%$, similar to that usually found in Seyfert 2 galaxies (e.g. Turner et al. 1997).

At the spectral resolution of the *Beppo*SAX MECS, the Gaussian line at $\sim 6.4$ keV is unresolved with a rest frame energy position of $6.42 \pm 0.13$ keV and an observed equivalent width (EW) of $636^{+236}_{-270}$ eV. This value is significantly larger than that observed in Seyfert 1 galaxies (EW$= 230 \pm 60$ eV, Nandra et al. 1997) but is similar to that measured in Seyfert 2 galaxies (e.g. Bassani et al. 1999). The measured position is not consistent with He-like (6.7 keV) or H-like (6.96 keV) Fe, as expected if the line were produced inside the warm, highly ionized gas which scatters the primary AGN spectrum. However it is consistent with the low ionization Fe-K$\alpha$ line from cold material. This in turn leads to two possibilities: the line could be produced by a reflected and/or a transmitted component[4]. The first

[4]It should be recalled that Fe-K$\alpha$ emission is also typical of High Mass X-ray Binaries (HMXBs) spectra (White et al. 1983). However, its equivalent width, either observed directly

possibility however is unlikely since a significant reflection component cannot be easily accommodated within the *Beppo*SAX data (using the PEXRAV model, the 90% upper limit on the reflection fraction is 0.07). The second possibility invokes the production of the cold Fe-K$\alpha$ line by transmission through the same absorbing medium that affects the primary AGN continuum: indeed, the EW measured with respect to the transmitted component, $\sim 7$ keV, is consistent (within the errors on the intrinsic $N_H$) with what is expected from transmission (see e.g. Leahy and Creighton 1993), making this possibility highly plausible. We note here that the absorbing medium in composite starburst-AGN galaxies, such as Arp 299, is not univocally associated to the putative absorbing torus but the nuclear starburst itself could be a significant source of absorption (Fabian et al. 1998; Levenson, Weaver and Heckman 2001). The measured EW (with respect to the transmitted component) for Arp 299 line is a factor $\sim$ 3-4 above the prediction from the model in Ghisellini et al. (1994) obtained using a simple toroidal geometry, which is a strong hint towards assuming the above argument apply.

Finally, the unresolved Gaussian line at $3.38^{+0.16}_{-0.13}$ keV (EW$\simeq 125$ eV) is consistent with the ArXVIII K$\alpha$ line. This line, which originates in the hot scattering medium itself (e.g. Netzer, Turner and George 1998), has been observed also in the Compton-thick Seyfert 2 galaxy Circinus (EW$\sim$ 60 eV; Sambruna et al. 2001). Based on the flux ratio between the ArXVIII K$\alpha$ line and the Fe He-like line (which should be produced inside the same hot scattering medium) observed in Circinus, in Arp 299 we would expect an Fe He-like line with EW $\sim 400$ eV, a value consistent (within a factor of 2) with the derived 90% upper limit.

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in HMXBs (typically EW $\sim 0.3$ keV: see White et al. 1983) or inferred for galaxies with X-ray emission dominated by HMXBs (Persic & Rephaeli 2002), is inconsistent with the large value observed here (if the emission has to be completely accounted for by HMXBs).

### 4.2. The Starburst Component

The best-fit soft X-ray thermal component gives a $kT \simeq 0.86$ keV. This value is consistent, within the errors, with that previously obtained by ZGW98 and H99 using ROSAT PSPC plus ASCA data. It is also similar to that usually found in other well studied starburst galaxies (e.g. Dahlem, Weaver and Heckman 1998). This thermal emission likely originates from the interaction between hot, low-density galactic winds and cold, high-density ISM (see H99).

Starburst galaxies are also characterized by a hard 2–10 keV spectral component interpreted as being either thermal with $kT \sim 5-10$ keV or non-thermal with $\Gamma \sim 1.5-2$ (e.g. Dahlem, Weaver and Heckman 1998). Such hard component is likely to be the integrated emission of X-ray binaries, and can be modelled by means of a cutoff power-law, $f(E) \propto E^{-\Gamma}e^{-E/kT}$ (CPL model, see Persic and Rephaeli 2002).

In order to check to what extent the 2–10 keV emission from Arp 299 can be related to the starburst, in our model we have replaced the scattered AGN component (labelled as *b* in section 3) with: *a)* a thermal component or *b)* the absorbed CPL model under the hypothesis that the main contribution is due to X-ray binaries. Both alternatives are statistically viable, with: *a)* the thermal model with $kT = 6.58^{+1.74}_{-1.18}$ or *b)* the unabsorbed CPL model with $\Gamma = 1.65 \pm 0.15$ ($kT$ fixed at 8 keV). In both cases, the spectral parameters of the soft X-ray component and of the absorbed AGN component remain consistent (within the errors) with those reported in Table 1. Since the inferred 2–10 keV luminosity of both the thermal and the CPL components is $\sim 2 \times 10^{41}$ erg s$^{-1}$ (reasonable for a bright FIR galaxy like Arp 299 ) we cannot rule out that at least part of the observed 2–10 keV X-ray luminosity is due to the X-ray binaries directly associated with the starburst (which may also contribute to the observed Fe-K$\alpha$ emission) [5] . This conclusion was reached by ZGW98 and H99 using ASCA data. However the ASCA statistics and energy coverage were insufficient to clearly detect the 6.4 keV Fe-K$\alpha$ emission line and to reveal the high energy bump [6]. The new broad-band *Beppo*SAX data instead clearly require the presence of an absorbed AGN component.

## 5. Conclusions

In a *Beppo*SAX observation of the merging starburst system Arp 299 the 0.1–40 keV data coverage clearly reveals, for the first time in this system, the presence of a deeply buried ($N_H \simeq 2.5 \times 10^{24}$ cm$^{-2}$) AGN with an intrinsic (i.e. unabsorbed) luminosity of $L_{0.5-100 \text{ keV}} \simeq 1.9 \times 10^{43}$ erg s$^{-1}$. This AGN component was missed in previous multiwavelength observations. Assuming a Galactic standard value of $E_{B-V}/N_H = 1.7 \times 10^{-22}$ mag cm$^2$ (Bohlin et al. 1978) and the measured $N_H$ value we argue that the AGN is completely absorbed in the optical and IR band ($A_V > 1000$ mag!!).

The intrinsic AGN's X-ray luminosity is a factor $\sim 50$ less than $L_{FIR}$ ($\sim 10^{45}$ erg s$^{-1}$). Thus the total FIR luminosity of the system cannot be entirely associated to the AGN even assuming an AGN UV luminosity a factor $\sim 10$ greater than the X-ray luminosity (as observed in QSOs, e.g. Elvis et al. 1994). This suggests that the bulk FIR emission may be due to the starburst, in agreement with the results obtained by Laurent et al. (2000) using

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[5]If this is the case, than the AGN scattered flux fraction reported in section 4.1, $(5\pm3)\%$, should be considered as an upper limit.

[6]We have directly verified that the archival *ASCA* data are consistent with the best fit spectrum reported in Table 1 and are not deep enough to clearly detect the 6.4 keV Fe-K$\alpha$ emission line.

5-16$\mu$m ISOCAM data. This conclusion may also be supported by the fact that the ratio of the soft X-ray thermal emission (likely associated with the starburst) to the FIR emission ($\sim 10^{-4}$ in the case of Arp 299) is similar to other "bona fide" starburst galaxies such as M82 ($\sim 6 \times 10^{-5}$) and NGC 253 ($7 \times 10^{-5}$).

A question unsolved at the present stage is the location of the AGN inside the interacting system Arp 299. At the spatial resolution of the *Beppo*SAX instruments we are collecting photons from Arp 299 (= IC694 + NGC 3690) as well as from the nearby galaxies Arp296 and MCG+10-17-2a. It is safe to exclude the last two as the origin of the hard X-ray emission since they are very weak sources in both the radio and in the IR, and they were not detected in soft X-rays by ZGW98. On the other hand both IC694 and NGC 3690 could be the host of the AGN. We have recently retrieved the public *Chandra* and XMM-Newton data for this system. From a preliminary analysis a strong line at $\sim 6.4$ keV is clearly present in NGC 3690 and maybe also in IC694, suggesting the possible presence of two AGNs. The results of this analysis, which will also include an estimate of the binaries contribution to the 2-10 keV emission and a detailed comparison of the X-ray emission with that at other wavelenghts, will be reported in a forthcoming paper.

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AAS LaTeX macros v5.0.

## Figure Captions

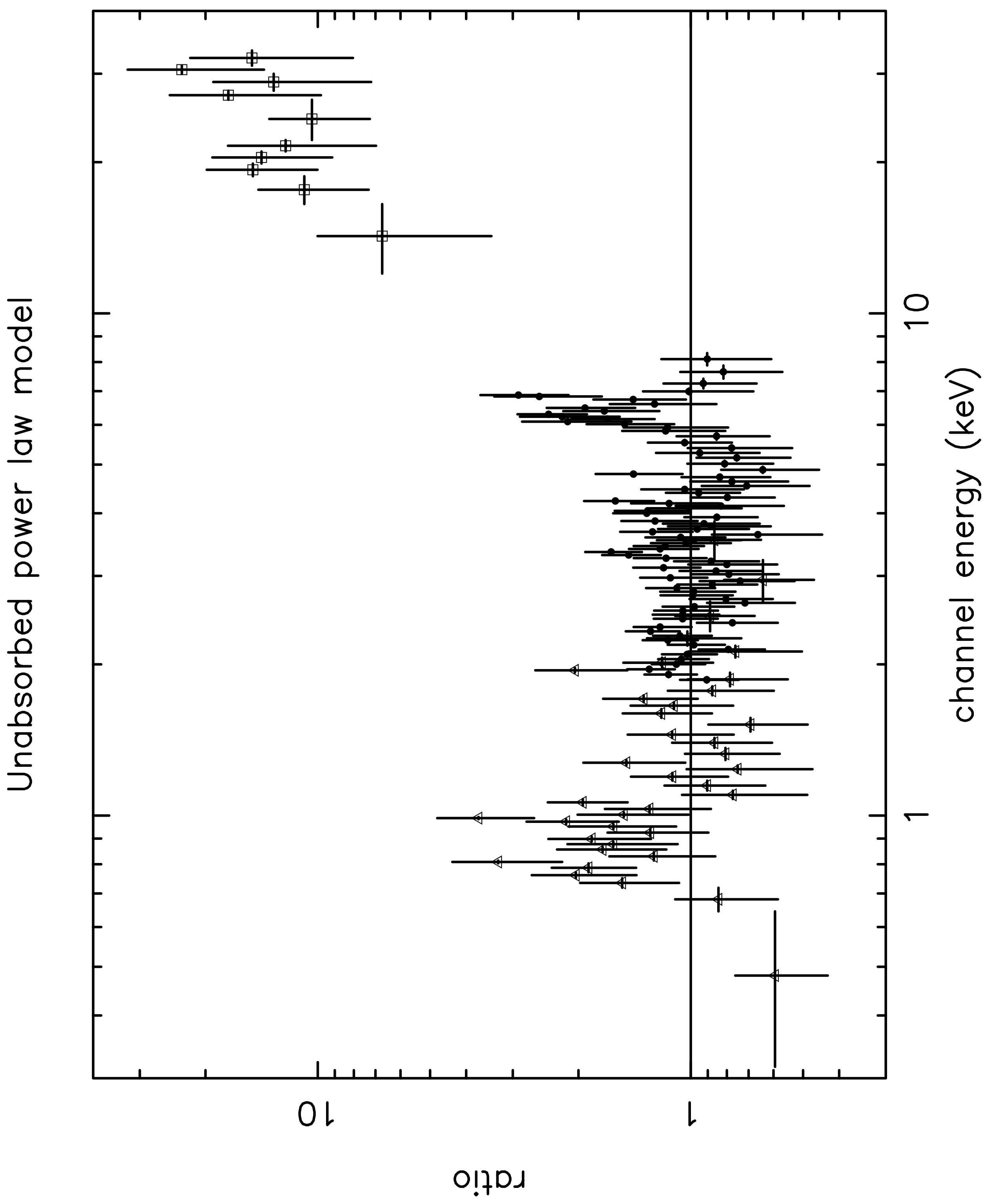
Fig. 1.— Ratio between the unabsorbed power-law model and the *Beppo*SAX LECS (open triangles), MECS (filled circles) and PDS (open squares) data. The PDS to MECS normalization factor is constrained to vary within the range indicated by the *Beppo*SAX Cookbook (Fiore et al. 1999).

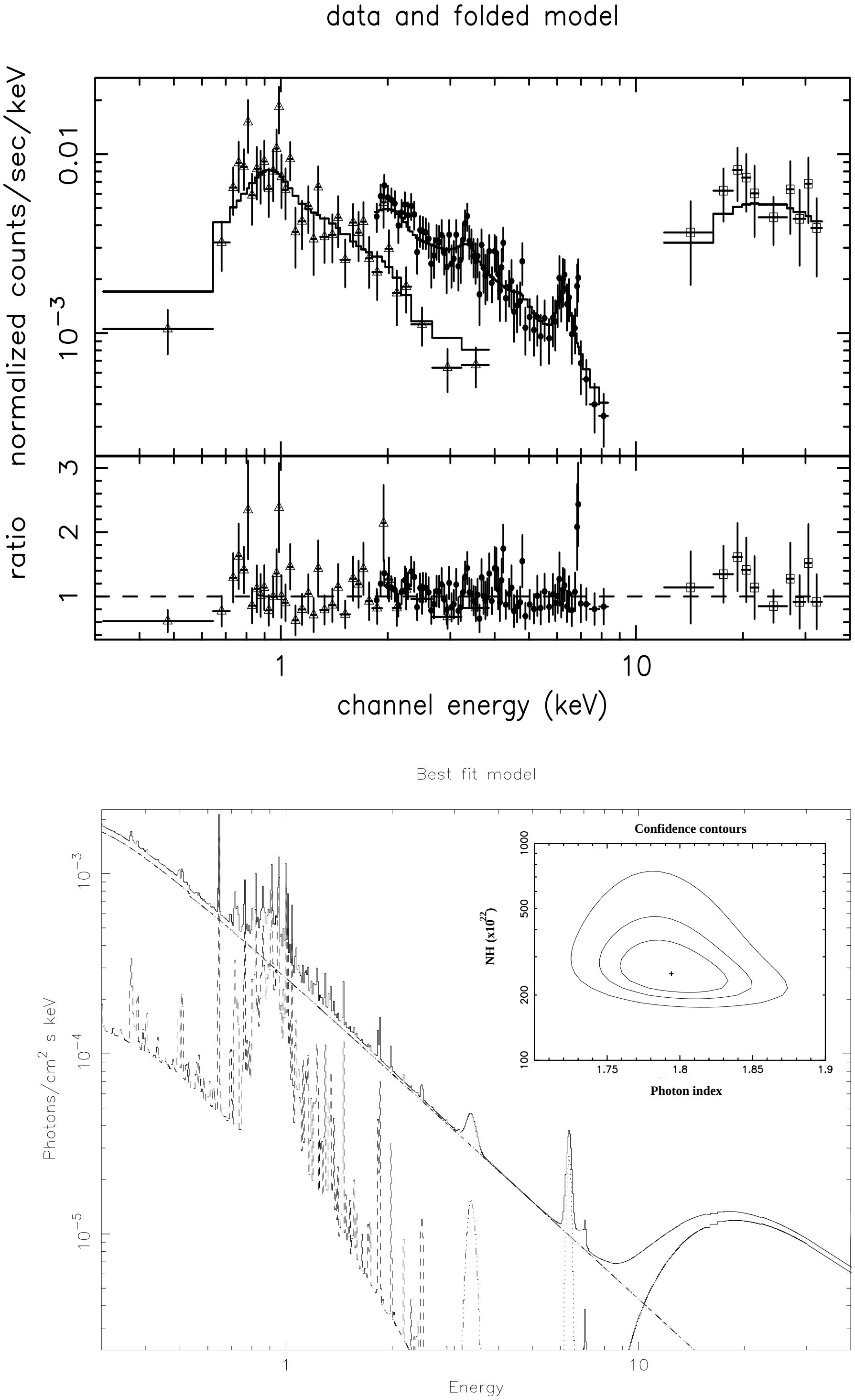
Fig. 2.— Data fit with a MEKAL thermal component, the “leaky-absorber” continuum and two narrow Gaussian lines (see Table 1). *Panel a*: LECS (open triangles), MECS (filled circles) and PDS (open squares) folded spectra and data; *panel b*: ratio between the data and the best-fit model; *panel c*: the unfolded model. *Panel c insert:* confidence contours (68%, 90% and 99% confidence level for two interesting parameters) for the power law photon index and the absorbing column density.

Table 1: Results of the spectral fit (LECS+MECS+PDS): MEKAL thermal component + absorbed and scattered power law + narrow Gaussian lines ($\chi^2$/d.o.f=104.2/118), and unabsorbed X-ray luminosities

| | | $kT$ (keV)/$\Gamma$/$E_{\rm line}$ (keV) | Norm | $N_H$/EW (eV) | Luminosity (erg s$^{-1}$) | | |
|---|---|---|---|---|---|---|---|
| | | | | | 0.5–2 keV | 2–10 keV | 10–100 keV |
| SB | MEKAL$^{(a)}$ | $0.86^{+0.24}_{-0.19}$ | $10.29^{+5.98(b)}_{-4.63}$ | | $1.12\times10^{41}$ | $7.41\times10^{39}$ | $5.36\times10^{35}$ |
| AGN | Absorbed P. L. | $1.79^{+0.05(c)}_{-0.03}$ | $590^{+523(d)}_{-169}$ | $2.52^{+1.39(e)}_{-0.56}$ | | | |
| | Unabsorbed P. L. | $1.79^{+0.05(c)}_{-0.03}$ | $26.93^{+4.29(d)}_{-3.93}$ | | $3.09\times10^{42}$ | $4.93\times10^{42}$ | $1.06\times10^{43}$ |
| | Lines (rest frame) $^{(f)}$ | $3.38^{+0.16}_{-0.13}$ | $0.39^{+0.30(g)}_{-0.26}$ | $125^{+98}_{-84}$ | | | |
| | | $6.42^{+0.13}_{-0.13}$ | $0.68^{+0.29(g)}_{-0.26}$ | $636^{+236}_{-270}$ | | | |

NOTE: Errors are quoted at the 90% confidence level for 1 parameter of interest ($\Delta\chi^2 = 2.71$). The LECS to MECS and PDS to MECS normalization factors (0.7 and 0.95, respectively) are consistent with the known differences in the absolute calibration of the instruments. The total observed fluxes of Arp 299 are $8.16 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$(0.5–2 keV), $1.13 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$(2–10 keV) and $3.23 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$(10–100 keV). $^{(a)}$ The metallicity of the thermal component was fixed to the Solar one. $^{(b)}$ In units of $[10^{-19}/(4\pi D^2)\int n_e n_H\, dV]$ @1 keV, where $D$ is the distance of the source in cm, $n_e$ and $n_H$ are the electron and $H$ density in units of cm$^{-3}$, and $V$ is the volume filled by the X-ray emmitting gas in cm$^3$. $^{(c)}$ The two power law photon index have been fitted together. $^{(d)}$ In units of $10^{-5}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ @1 keV. $^{(e)}$ Column density of neutral hydrogen (in units of $10^{24}$ cm$^{-2}$) in addition to $N_{H,Gal} = 9.92 \times 10^{19}$ cm$^{-2}$. $^{(f)}$ The lines are unresolved at the spectral resolution of the *Beppo*SAX MECS. $^{(g)}$ In units of $10^{-5}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at the energy of the line.


Unabsorbed power law model
channel energy (keV)
1
10
ratio
1
10


data and folded model
normalized counts/sec/keV
0.01
$10^{-3}$
ratio
3
2
1
1
10
channel energy (keV)
Best fit model
Photons/cm$^2$ s keV
$10^{-3}$
$10^{-4}$
$10^{-5}$
1
10
Energy
Confidence contours
NH (x10$^{22}$)
1000
500
200
100
1.75
1.8
1.85
1.9
Photon index

a)

b)

c)